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Reply on RC3

Henrike Schmidt et al.

Author comment on "Causes of uncertainties in the representation of the Arabian Sea oxygen minimum zone in CMIP5 models" by Henrike Schmidt et al., Ocean Sci. Discuss., https://doi.org/10.5194/os-2021-36-AC3, 2021

General comments:

This paper aims to assess the representation of the Arabian Oxygen minimum zone

(ASOMZ) in 10 CMIP5 model historical simulations and relates the error to water mass properties. The topic is interesting and important. However, there are several major issues that should be addressed. The authors stated that none of the selected CMIP5 ESMs reproduces the observed oxygen distribution. It would be interesting to examine these aspects in their upgraded CMIP6 versions to check if they had substantially improved or worsen in representing OMZ and water mass properties.

The water mass properties over the north Indian Ocean region and their implications on ocean biogeochemistry in CMIP models have not been studied extensively. This paper presents important and fresh perspectives through the use clustering and quantification of uncertainties in water mass mixing ratios. However, the paper has not been written clearly. This manuscript was not structured well, especially the introduction and results sections. Introduction needs to be organised. Re-structuring of the manuscript can be done to make it easily readable and highlight the novelty of the study. I would recommend a major revision.

Reply to reviewer #3

We would like to thank the reviewer for taking the time and for providing constructive and very specific comments, which will help to improve the manuscript considerably.

We agree with the reviewer that it would be interesting to examine these aspects also for the upgraded CMIP6 models. However, we do not find it advisable to include the analysis of the CMIP6 models in this study. First of all, for a meaningful discussion of our results the previous work done on CMIP5 models by other scientists was important. This enables us to set our results into perspective and to draw conclusions. However, for the relatively new set of CMIP6 models, such a base is so far not available. Second, the protocols for the new CMIP6 models differ from the older CMIP5 ones. With this, they form a new

and independent set of experiments and cannot be treated identically to CMIP5. Therefore, a comprehensive discussion and interpretation of the results is only possible to a very limited extent. However, we are aware of the importance to fully investigate the CMIP6 models, therefore we included all relevant available information (and the respective references) in the discussion.

We will revise the introduction and make sure that the novelty of the study is clear throughout the manuscript.

We have carefully addressed all the comments. The point-by-point responses to the specific comments follow below.

Specific comments:

- Why did the authors choose 50 threshold to define OMZ? Please clarify in the methodology section.

Unfortunately, this is a misunderstanding. We did not choose an oxygen threshold for the analysis but used averaged oxygen profiles in order to be able to compare the OMZs in a way that is as generally valid as possible. The thresholds that are mentioned in the text are used to make different statements, as the behaviour among the models show systematic differences when accounting a specific threshold. We will clarify this in the revised manuscript.

In the methods section page 5, line 11-13 we explained the choice of this threshold for the plot. To prevent misunderstandings, we will rewrite the sentence: "For a first spatial comparison, we chose our threshold to be 50 µmol l−1 to make it comparable to previous studies on CMIP5 oxygen distribution (e.g. Cabré et al., 2015; Cocco et al., 2013) and looked at the horizontal extension of the OMZ dependent on depth and the actual location of these areas in a map."

In addition, we add two vertical lines to Figure 4a for more clarity. With this modification, all thesholds that are mentioned in the text are included in Fig 4a.

- Are there any criteria adopted in selecting the specific ESMs? Are they good at representing the Arabian Sea mean state? Provide references if available.

No, there are no criteria for the selection of the models. We chose the 10 models from the CMIP5 models that provided oxygen data for the historical period. We will clarify that in the revised manuscript: "In this study we included all ESMs from the CMIP5 project (Taylor et al., 2012), where output of dissolved oxygen was available. The suit of ten model simulations includes …"

As we focus on oxygen, we give an overview of the oxygen mean state in these models (Fig. 4) and see that they are not that good in representing it. Other variables and processes connected to the representation of the OMZ in the Arabian Sea that were already analysed for the CMIP5 models were referenced in the discussion.

- Description of OMZ along west coast of India can be included in the introduction section.

Thank you for your suggestion. We are aware of the coastal OMZ and the complex dynamics right off the west coast of India. However, the resolution of the ESMs used in this study is too coarse, so coastal processes are not fully resolved and the model bias in these areas is expected to be large. We therefore excluded the coastal areas for the determination of the clusters and focus on the open ocean OMZ.

We will briefly discuss this point in the introduction and emphasis the central Arbian Sea as the focus area of this study.

- The description of mixing ratio coefficients is not clear. Please elaborate. Define in terms of their corresponding water mass.

We will specify the description of the mixing ratio coefficient in the revised manuscript, and we will explicitly mention the corresponding water masses used in this context:

… 'The three main source water masses in the AS are IODW, RSW/PGW and ICW (Fig. 2). We used a linear mixing approach and restricted the input to physical water mass properties from observational data. By considering potential temperature (θ), salinity (S) and mass conservation this yielded the possibility to resolve the mixing ratio of the three main source water masses in the AS. The set of linear equations was:

$$\theta=\alpha\theta(IODW) +\beta\theta(ICW) +\gamma\theta(RSW/PGW) \quad (1)$$

$$S = \alpha S(IODW) + \beta S(ICW) + \gamma S(RSW/PGW) \quad (2)$$

$$1=\alpha+\beta+\gamma \quad (3)$$

α, β and γ were the mixing ratio coefficients for IODW, ICW and RSW/PGW, respectively.'

- Apart from the errors associated with ventilation, it would be interesting to describe the static stability and solubility parameter in these models. Stratification of upper layers associated with warming and weakened surface winds restrict mixing oxygen-rich surface waters to intermediate depths, leading to oxygen depletion. Please clarify.

That is a good point that was mentioned as well by reviewer #2. We will compute oxygen solubilities and analyze corresponding model-data differences and will add these findings to the revised manuscript. We will also compare the static stability in the upper layers and discuss the findings in the revised manuscript.

- Page 5, line 10: "We chose our threshold to be 50 ". But a threshold of 60 is referred to state the general underestimation of OMZ volume (e.g.: Abstract section). Please clarify.

As explained above (see point 1), we did not choose a single oxygen threshold for the analysis. In the discussion we state that "All ten models underestimate the ASOMZ volume when we consider oxygen thresholds of 60 µmol l−1 or higher (Fig. 4a)." This is just the threshold that fits the statement and is not related to the Figures 4b & c.

To avoid further misunderstanding, we also added the two thresholds of 20 and 60 µmol l−1 to Fig. 4a.

- Page 16, line 5: "…….physical model components show no obvious deficiencies in circulation and mixing". The analysis presented in this paper is not sufficient to conclude this. Please clarify.

We would like to apologise, as this sentence was misleading. We wanted to say that the physical models show deficiencies, but that these are not large enough to adequately explain the deviations in oxygen. We will rephrase it in the revised manuscript.

Technical corrections:

Page 4, line 20: "……..OMZ between 200 and 1800m". Provide references.

The concrete depth of the OMZ depends on the oxygen threshold and varies among the models. Thus, there are various depth ranges related to the OMZ. We neglected that fact while writing such a general statement that refers to the observations and the threshold of 50 µmol l−1. We apologize for that and will rewrite this sentence:

'Averaging also neglects the seasonal cycle. The seasonal oxygen cycle is weak in the upper layers of the AS and not noticeable at greater depth (Schmidt et al., 2020). Thus, averaging is a reasonable approach for a uniform process analysis over large parts of the water column.'

Page 4, line 25: "…….depth levels ranges from 31 to 63". Please rewrite this sentence. What are the numbers 31 and 63?

The numbers are the numbers of resolved depth levels in the models. We rewrote the sentence to make that clear: 'The horizontal resolution ranges from 2° x 2° to 0.4° x 0.4° and the vertical resolution varies between 31 and 63 resolved depth levels.'

Page 5, line 10: "We thus compare the volume of the OMZ for a wide range of thresholds." Please provide the values.

We included the values and the new sentence is: "We thus compare the volume of the OMZ for a range of thresholds from 0 to 100 µmol l−1."

Page 5, line 25: "…….Oxygen profiles in the AS for all models and the observations." All models or selected ESMs?

With all models we mean all the 10 models considered for this study. We changed the sentence to avoid misunderstandings: "We performed the cluster analysis for oxygen profiles in the AS for all 10 models considered in this study and the observations."

Page 5, line 30: Is that the area shown in Fig. 4c? The location of the central AS can be better shown on a map.

Yes, that is the area marked in Figure 4c. We will include the information to the text and reference the Figure accordingly: 'For this analysis we chose to exclude coastal areas and focus on the open ocean core of the ASOMZ in the central AS between 16 and 22 °N, 61 and 67 °E and from 10 to 1800 m depth and analysed averaged profiles in this region, that is marked in Figure 4c.'

Page 6, line 30: "…… three different source water masses". Please mention three source water masses.

We will mention them here: 'The three main source water masses in the AS are IODW, RSW/PGW and ICW (Fig. 2). We used a linear mixing approach and restricted the input to physical water mass properties from observational data. By considering potential temperature (θ), salinity (S) and mass conservation this yielded the possibility to resolve the mixing ratio of the three main source water masses in the AS.'

Page 7, line 5:" ……IODW, RSW and PGW and ICW". Please rewrite this sentence. Should it be like……PGW/RSW? Please provide proper references to the methods described to determine the source water masses (Page 7, line 5-15).

We apologize for the deficient description how we determined the source water masses. We will restructure and rewrite parts of that section to make our methods more comprehensible (see also point 4):

… 'were the mixing ratio coefficients for IODW, ICW and RSW/PGW, respectively. The equations were solved at each data grid point.

To solve the equations the temperature and salinity input of the source water masses has to be determined first. Therefore, we used values from the literature that are based on observations (Table 2, Fig. 3a) and solved the equations for each observational WOA13 data grid point in the box in the ASOMZ (Fig. 3b). Figure 3b shows now mixing ratios for the upper 200 m in the AS. This is due to the limitations of the analysis method: It is not possible to mix the source water masses in a realistic way and get a higher/lower temperature and salinity than the highest/lowest temperature and salinity input of the source water masses. With the input of the described three source water masses this limits our analysis results to the central AS and thus the core region of the ASOMZ, which is of the main interest of this study. In the models the source water properties deviate from the observations. To obtain an uncertainty range of the water mass

analysis that can be related to such a change of the input, we solved the equations again for each observational WOA13 data grid point in the box in the ASOMZ. This time we used arithmetic temperature and salinity mean of the WOA13 data in the IO, following the calculations described in section 3.3 for oxygen (Fig. 3c & d). This allows us to draw conclusions on the uncertainties in the mixing in those models.'

Provide references or describe the method to obtain the age of water masses in selected models (Page 9, line 30).

We will include the method how we obtained the age of the water masses in the models: 'To find out more about the differences between clusters in the oxygen consumption of IODW on the way to the AS, we looked at the age since surface contact of two models. Age since surface contact is an ideal age tracer that is included only in two of the considered ten model data sets. We obtained the age of IODW in the Southern Ocean by the arithmetic mean of all grid boxes of the formation region of the source water mass, similar to the calculation of the oxygen content (section 3.3). In the deep AS the age is calculated by the mean within the averaging box of the profiles (Fig. 5) below 1800 m depth.'